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by David S. Kleponis, Audrey L. Mihalcin, and Gordon L. Filbey, Jr.

ARL-RP-92 **April 2005**

A reprint from the *14th Engineering Mechanics Conference*,
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14. ABSTRACT

Computational modeling is used to derive desired through-thickness gradients in material strength for optimal performance of functional gradient materials as armors. The basic thesis is that one does not know a priori what variation in a given material property, such as hardness or yield strength, is necessarily the best choice for optimal ballistic performance in a tailored armor material. Choices for how such a property should be distributed may exist, but attempting to fabricate and experimentally test every possible choice is not the most efficient way to proceed to answers.

A common fabrication procedure for such materials is to build them in layers, which allows one to change materials somewhat from layer to layer. In order to gain confidence in designing the thickness of various layers and the desired material properties, we first modeled computationally the ballistic performance of layered steel constructs with the Eulerian wave code CTH. The layered steel calculations revealed surprising trends as related to the distribution of strength properties among the various layers, as well as for the limit-layer thickness. Conventional wisdom of “hard-to-soft” is not necessarily the optimal answer.

15. SUBJECT TERMS

functional gradient materials, layered media, hard steel armor, armor mechanics

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MATERIAL DESIGN PARADIGMS FOR OPTIMAL FUNCTIONAL GRADIENT ARMORS

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1. **INTRODUCTION**

An assumption frequently made in choosing material property distributions in functionally graded material (FGM) armors is that the hardest and strongest layer should be at the front of the target. That is, maximum protection should be achieved when the hardest and strongest layer is the first element touched by the attacking penetrator. The experience base of dual hard steel armors of the 1960s and the typical arrangements of SiC or Al2O3 tiles mounted on fiber-composite or aluminum substrates over the past thirty years support this view. More recent views of what might constitute an optimal armor that employs ceramic materials is that advantages can be realized by layering elements of different materials and properties. Advances in materials processing now allow the fabrication of graded materials, typically resulting in (but not limited to) discrete layers through the thickness. In terms of strengths and hardness, materials experts have often attempted to produce a material with linearly decreasing properties progressing through the thickness. It appears that this reasoning on how to vary properties is driven by the dual-hard and the ceramic-on-soft-substrate experience.

A partially conflicting view to this layering presentation against an attacking penetrator comes from the experiments of Hauver et al. [REF]. This work demonstrates dwell phenomenon at the front surface of brittle ceramic targets, in which the attacking penetrator does not proceed into the target but rather flows laterally on the front surface in a manner similar to a water stream hitting a steel plate. Their research studied conditions under which a period (dwell time) of non-penetration can be established at the front surface. It is found that a region of soft material on the front of the target can actually greatly enhance the performance of certain ceramic targets. Heuristically, the phenomenon can be thought of as pre-compressing the ceramic and preventing strong loading shocks from forming that could lead to premature tensile unloading conditions from any of the ceramic boundaries, including the front, first struck surface. Hauver et al. experiments were usually in heavily confined ceramic conditions, including the rear surface. Dehn [REF] obtained computational results, agreeing favorably with experiment, that support this understanding of dwell phenomena.

It would thus seem that guidelines for material ordering could be established, either with semi-empirical engineering or with computational models, to guide the materials engineer in layering objectives that yield the maximum benefit to armor performance. This premise is examined with the solid-mechanics wave-propagation code CTH, for all

iterations of materials layering, using the computational horsepower available at the Aberdeen Major Shared Resource Center.

It is shown that once a rational problem configuration is established, the best target performance is not obtained with the conventional wisdom of placing the hardest material at the front of the target. This is found when targets are comprised of a range of materials from weak to strong, and depth-of-penetration (DOP) metrics are used. Best results from an armor point of view are generally to start with the softest at the front and build monotonically to the hardest layer laid intimately against thick Rolled Homogeneous Armor (RHA) backing material. The residual penetrations are measured into this RHA backing. It is also illustrated that layer thickness of target material less than the diameter of the attacking penetrator have little significant effect on the final penetration result. This too is an important result for the materials engineer. Although most of the results presented are derived for a hemispherical nose penetrator at several impact velocities, results are also given for blunt-ended and ojival-nose penetrators.

2. PROBLEM CONFIGURATION

Given that the materials engineer can tailor FGMs, what are the optimal gradients to choose for strength, toughness, ductility, and possibly density, such that ballistic performance is maximized? And how broadly tuned is the designer FGM to a range of threats? Thought must also be given as to which performance parameter is to used, whether DOP into a contiguous backup material, or residual length and velocity of the penetrator following a spaced FGM element, or total path weight of the armor required to defeat the penetrator. The approach chosen was to calculate residual depth-of-penetration (DOP) into Rolled Homogeneous Armor (RHA) placed in intimate contact with the FGM material, using the solid-mechanics wave-propagation code CTH. To illustrate an optimal FGM taxonomy, a constant thickness region of constant average strength was chosen for the candidate layered target. The plan is to subdivide the region into 2,3,4,6 and 12 levels of strength, which in every case average to the strength chosen for a monolithic material. With a good experience base in armor steels, and an opportunity to experimentally check the code prediction, the first calculations were made for layered hard steel targets. The Johnson-Cook visco-plastic deformation law was chosen to represent the plastic large deformation plasticity region. This can be written as follows for the flow stress **Y**:

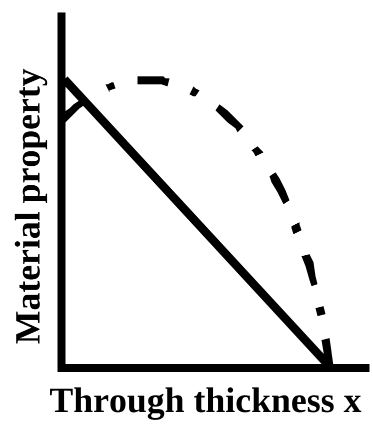


Figure1. Through-thickness variations

$$Y = \left(ajo + bjo \cdot e^{njo}\right)\left(1 + cjo \cdot \ln e^{*}\right)\left\{1 - \left(\frac{T - T_{room}}{Tjo - T_{room}}\right)^{mjo}\right\} \qquad where\ e^{*} = \frac{\dot{e}}{1/s}$$

For the various strength level representations, it is reasonably accurate to vary only the single parameter **ajo** (the initial flow stress when the strain rate is 1/s) to represent the

different strength levels of hard steel armor. It is well established that “6-inch” RHA can be accurately depicted with an **ajo** of 0.62 GPa. For the optimization problem, we elected to represent the harder, stronger FGM surrogate as layered steel that has an average ajo of 1.0 GPa (order of 145 ksi.) All other Johnson-Cook parameters are kept the same as the “6-inch” RHA backing. The rationale for this is that work hardened materials, from a stress-stain curve perspective, act like the original material but with the location of the elastic modulus load line shifted increasingly to the right before intersecting the plastic portion of the original curve. The Johnson-Cook parameters for the “6-inch” RHA steel are shown in Table 1.

Table 1. Johnson-Cook parameters for “6-inch” RHA

	ajo	**bjo**	**cjo**	**m**	**n**	**Tjo**	**Poisson**
Value	0.62	1.685	4.35E-3	0.800	0.754	0.15364	0.294
Units	GPa	GPa	[-]	[-]	[-]	eV	[1]

The yield stress of the outer layers for two or more strength levels were always taken as **ajo**=1.38 GPa (order of 200 ksi) and **ajo**=0.62 GPa. For greater than two levels (three, four, six and twelve were considered), strength increments were made equal from layer to layer. The diagram in Figure 2 best illustrates this.

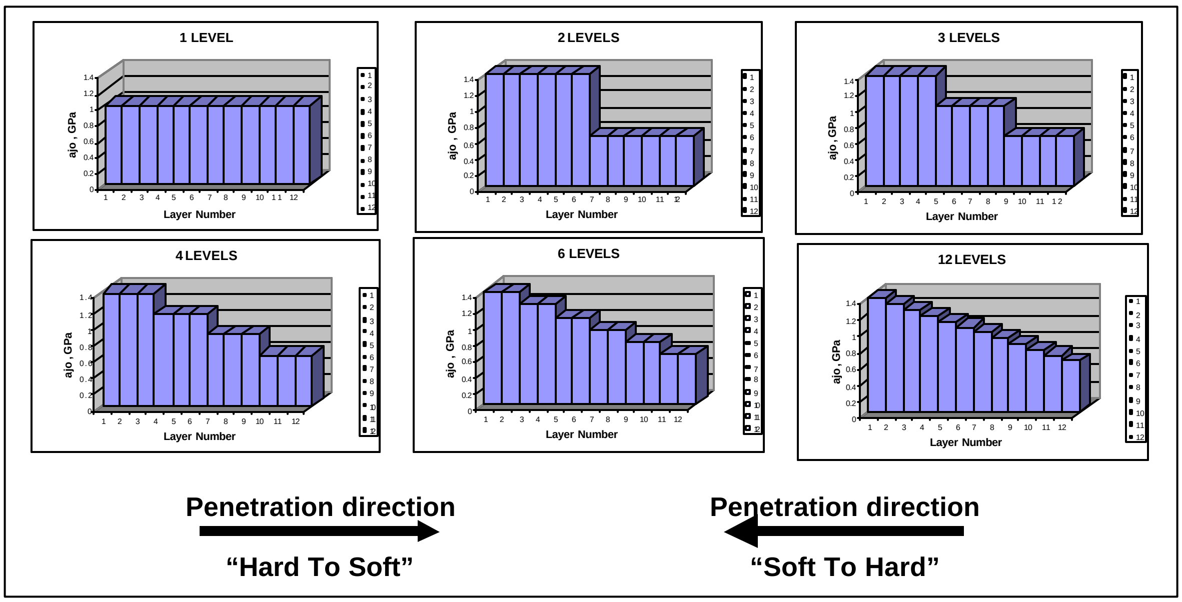


Figure 2. Depiction of strength levels chosen.

The Mie-Gruniesen equation of state is used to describe the dilatational portion of the deformation. The same values were used throughout for all strengths of steel considered, which is common practice in terminal ballistic computations.

3. LINEAR DISTRIBUTION RESULTS

These model constructs were computationally placed on thick “6-inch” RHA and tested for maximum depth of penetration when impacted by a hemispherical nosed, L/D =10

tungsten sintered metal (WSM) penetrator. Penetrator initial velocity was chosen as 1300 m/s, which allows a reality check with available published ballistic data. Depths of penetrations were initially calculated for "hard-to-soft" and "soft-to-hard" lay-ups, for the cases of two, three, four, six and twelve yield strength levels along the penetration direction. The surprising result is shown in Figure 3: ***for targets that operate by erosion, soft-to-hard strength levels of the layers provide better armor protection than does the conventional wisdom of hard-to-soft***. It is also noted in Figure 3 that at four or more levels of strength, there is little effect in the outcome by increasing the number of levels. This is related to the size of components in the experiment, and not controlled by directly by the number of layers. The four level case is shown in Figure 4. Penetrator dimensions control the sizing of components in the experiment. Once the penetrator size and striking velocity are chosen, the layered construct total thickness is controlled by the desire to have sufficient overmatch so that residual penetration into the "6-inch" RHA shows sensitivity to variations in the layering. With twelve layers, the consequences of these constraints are that the total thickness of the twelve layers shall be 31.75 mm and the layer thickness shall be 2.646 mm. This is very close to one-third the penetrator diameter, so that in this layered FGM simulant, ***strength levels along the penetration path that vary significantly in less than a penetrator diameter have little additional effect on the outcome of the experiment.*** This result has been obtained in another way by Segletes [REFS]. Segletes analytically examined the effect of periodic strength variation along a penetration path using a modified Tate procedure, and reached the same conclusion regarding fineness of material layers and their consequences on penetration behavior.

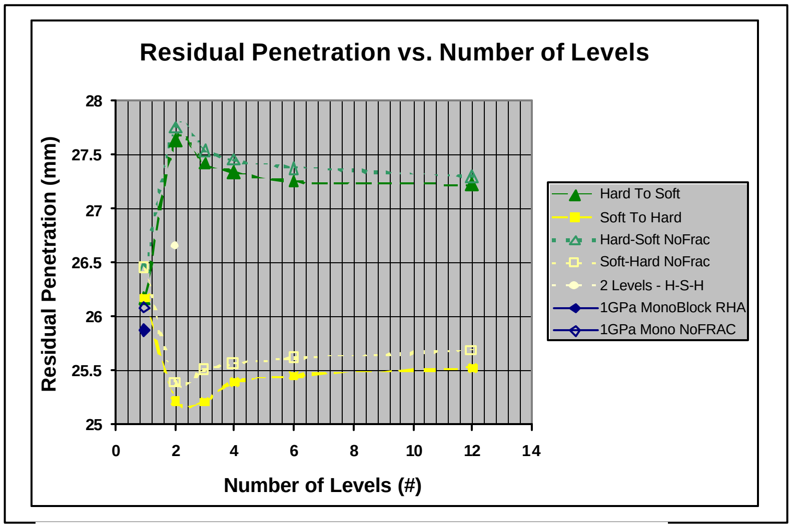


Figure 3. Results for linear strength distributions

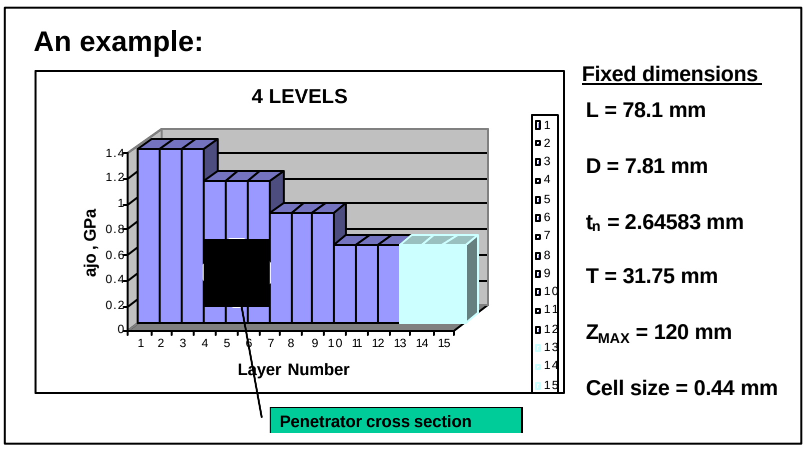
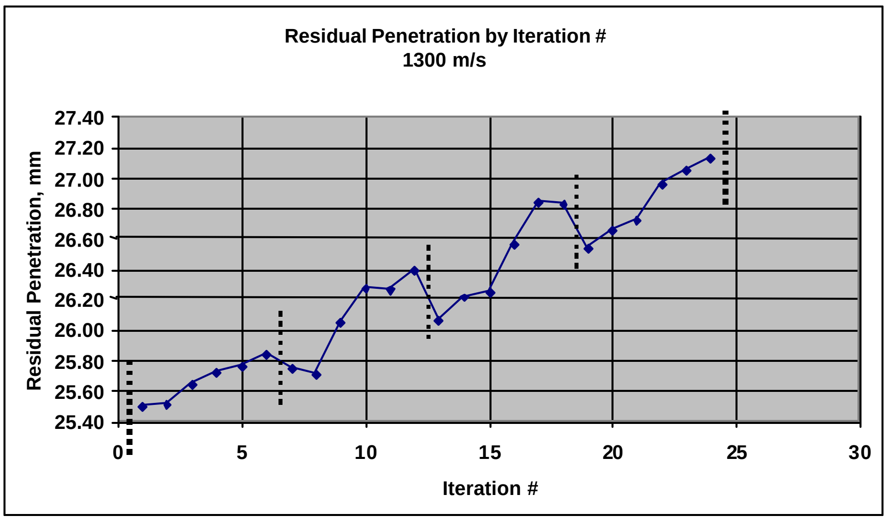


Figure 4. Problem sizing and dimensions

4. ALL-PERMUTATION RESULTS

The linear hard-to-soft and soft-to-hard are but two of the 4! = 24 permutations available in a target made of four hardness level items. Systematic iterations were done among the twenty-four possible stacking arrangements. These numerical experiments were repeated for striking velocities of 1050, 1125, 1300, 1375, and 1450 m/s, so that in all, 120 simulations were run. (Each simulation requires 9+ cpu hours on an SGI Origin 2000 class platform.) If one denotes the four asending strength levels as “1”, “2”, “3” and “4”, an iteration table can be prepared for all the possibilities. This table and the resulting maximum residual penetration are shown in Figure 5 for the 1300 m/s striking velocity case. The pattern of the results are generally quite similar among all the striking velocties; only one has been illustrated here.



Case #				
1	1	2	3	4
2	1	2	4	3
3	1	3	2	4
4	1	3	4	2
5	1	4	2	3
6	1	4	3	2
7	2	1	3	4
8	2	1	4	3
9	2	3	1	4
10	2	3	4	1
11	2	4	1	3
12	2	4	3	1
13	3	1	2	4
14	3	1	4	2
15	3	2	1	4
16	3	2	4	1
17	3	4	1	2
18	3	4	2	1
19	4	1	2	3
20	4	1	3	2
21	4	2	1	3
22	4	2	3	1
23	4	3	1	2
24	4	3	2	1

Figure 5. Residual penetrations by Iteration #. In the table, 1=Weakest and 4=Strongest material. “Case #” and “Iteration #” are equivalent.

A strong grouping of results by factor of six is evident in Figure 5. Although the 1300 m/s case is the one shown here, this pattern trend of rising throughout each group of six with or without slight reversals at the ends was evident at all impact velocities from 1150 m/s to 1450 m/s. Re-examination of the iteration table shows that the beginning element strengths are grouped by six elements each. That is, the first group of six all have the weakest material (“1”) first, then the second group of six have the second weakest material (“2”) first, etc. Internal ordering in each group almost always favors weakest material before a stronger one, as cross-examination of the graph and the table will reveal.

5. PENETRATOR NOSE SHAPE EFFECTS

Two extreme cases of nose shape geometry were examined. Results show that the trend of best armor performance by ordering the target layering from weak to strong continues to hold for these cases as well. The extremes considered were an equivalent mass WSM

right circular cylinder of identical diameter but slightly reduced length to compensate for replacing the hemispherical nose with a blunt end. Maximum residual penetrations are nearly identical to the hemispherical nose results, so that this order of change in nose geometry does not change the conclusion.

The other extreme is a different experiment, which is directly supported by a series of ballistic range tests with 0.50 cal AP (armor piercing) projectiles at full service velocity. The projectiles have a long ogival nose shape. In this case, the target was an originally homogeneous, high-strength-steel that had been induction zone hardened to produce two contiguous levels of strength through the thickness. The plate was 15 mm in total thickness, with an extremely hard (strong) front layer for 60% of the thickness (9 mm) and a less hard rear layer for 40% of the thickness (6 mm.) Results of simulations at 908 m/s (2800 fps) show slightly reduced DOP in Figure 6. The frames are shown at 130 microseconds, shortly after forward motion is arrested. Range experiments against plates simulated by this computation substantiate improved performance for soft-first. The ballistic limit velocity is about 100 m/s higher for the soft-first configuration than the hard-first configuration.

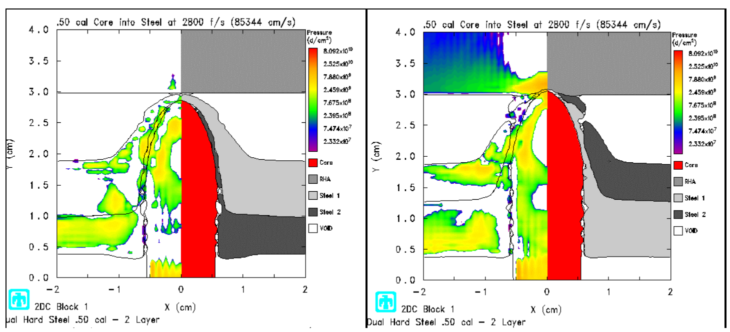


Figure 6. Differences produced by soft-first (left) and hard-first (right).

6. CONCLUSIONS

Ordering of strength levels is an important consideration in setting goals for functional graded materials for armor systems. Performance enhancements are available if conventional wisdom is ignored for more substantial evidence developed. It is demonstrated that for minimum depth-of-penetration, lower strength levels of an FGM layered construct should be the first the projectile impacts. It is also shown that strength level variations along the path occurring in less than a penetrator diameter have little effect on the penetration result.

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